A Way to Estimate the Discharge of the Melt Jet Flowing out of a Melting Furnace

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Abstract—A way to estimate the discharge of melt jet flowing out of a melting furnace is examined. We analyze the efficiency of algorithms for image matching in order to estimate the jet velocity. To decrease the time needed for estimating the 2D motion of melt flow, it is suggested to calculate the shift of 2D images according to two independent 1D projections. This approach makes it possible to estimate on-line the flow rate and to do it in television standard.

Keywords: a system of technical vision, melting furnace, melt jet discharge, image matching, image digital processing, cyclic invariants.

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INTRODUCTION

The modern industry of mineral wool production is characterized by high automation. All processes of raw material and fuel feeding including components completing, weighing, transportation, and feeding into a furnace are automated and performed according to a program. Special sensors determine and control the centrifuge's rotary speed, blowing temperature and humidity, and gas output. But several problems have not yet been solved, for example, the problem of how to consider the melt flow rate. Ordinary procedures for measuring the liquid flow rate are not suitable, since the medium is corrosive. The existing procedures for determining the melt flow rate are not efficient enough and do not meet the requirements on planning production cost. However, continuous checking on the melt flow rate is one of the most important problems for mineral wool production, since if the flow rate is overvalued, the raw materials and fuel are excessive, and if the flow rate is undervalued, the production quality drops. In any case, a sharp variation in melt flow rate is a symptom of any failure dealing with furnace operation. The melt flow rate should be monitored continuously making it possible to increase the production quality.

THE MAIN PART

To calculate the volume of material flowing out of the melting furnace for a certain period of time (melt discharge), it is necessary to know the material rate of motion within this period of time and the flow cross section. The problem on how to estimate the material rate of motion can be solved by a procedure for image recording. Under image recording we mean the process for determining the fragment position of one image in another one.

Let $f^e_M(x, y)$ be the image of material flow at time moment t_0. Let one of its $N \times N$ fragments, in particular, $f^e_N(x_e, y_e) = W_N(x - x_e, y - y_e)f^e_M(x, y)$ contain an image of the greatest relief segment of material flow, the coordinates of which coincide with the fragment center (x_e, y_e); we call it a reference fragment (Fig. 1).

In the next frame, we call it the current one $f^c_M(x, y)$; at the time moment t_1 the center of reference fragment

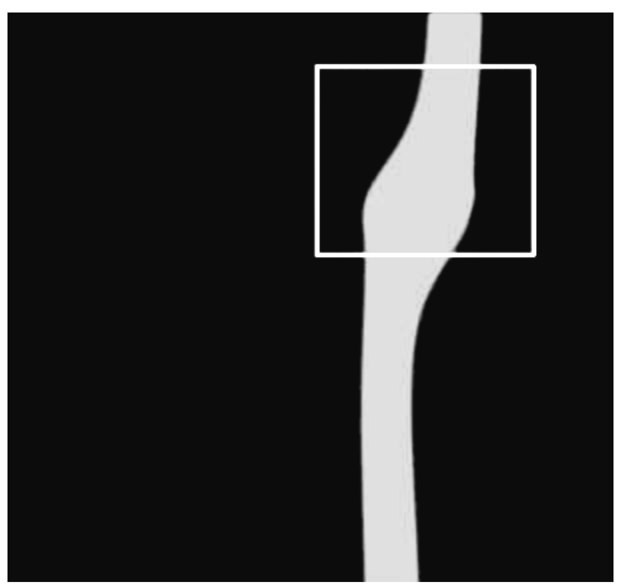

Fig. 1. Reference fragment of material flow.

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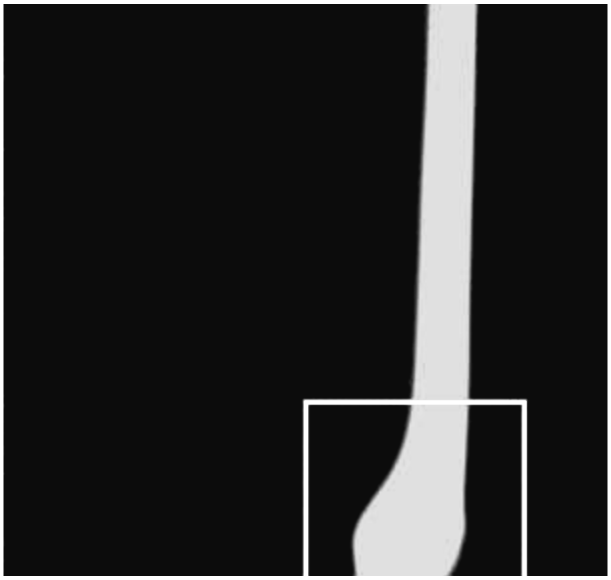

Fig. 2. Current fragment of material flow.

Fig. 3. Visualization of test image matching performed by hand.

$f_N^e(x_e, y_e)$ travels from point (x_e, y_e) into another one, for example, into point (u^*, v^*).

The procedure for image recording is as follows. The search for the $N \times N$ window W_N is scanned according to $f_M^c(x, y)$. In each position W_N separates fragment $f_N^c(u, v) = W_N(x - u, y - v)f_M^c(x, y)$ from the current image, for which the similarity with reference fragment $f_N^e(x_e, y_e)$ is determined. The position (u^*, v^*) of the search window $W_N(x - u^*, y - v^*)$ under which there is the greatest similarity between $f_N^c(u^*, v^*)$ and $f_N^e(x_e, y_e)$ makes it possible to determine the shift value of the reference fragment and the rate of motion for the material flow.

We reviewed algorithms for images matching with respect to the examined scientific field, in particular, for estimating the jet motion between two neighboring video frames, and we revealed that the most promising in terms of matching accuracy and computation complexity was the set of algorithms based on the measure of similarity μ between the reference $f_N^e(x, y)$ and current $f_N^c(u, v)$ signals. It was calculated by using the absolute difference method (MAD) [1]:

$$\mu[f_e, f_c, u, v] = \sum_{x=0}^{N-1}\sum_{y=0}^{N-1}\left|f_N^e(x, y) - f_N^c(u, v)\right|.$$

The modifications of this algorithm are as follows: the optimized strategies for searching for a global extremum for the measure of similarity are different [1–3]. Such strategies are three-step search, hexagonal search, and cross-hexagonal search.

To determine the accuracy of shift estimation, we programmed and simulated these algorithms mathematically. As test images we choose three typical subjects that present images of two sequential video frames (previous and current) of melt jet running out of the melting furnace. One such subject is presented in Figs. 1 and 2.

To verify the algorithms, we develop additional software that makes it possible to estimate by hand the shift of the jet image between two neighbor frames.

Figure 3 depicts the results of video frame matching performed by hand.

The quantitative characteristics obtained according to the experimental results are presented in the table. The size of the processed video frames is 768 × 576 pixels, and the size of the reference image is 250 × 250 pixels. The time of algorithm operation is averaged, since the OS WINDOWS is not an on-line operating system and it is impossible to measure exactly the time for executing one algorithm or another.

The examined procedures for estimating the shift of image $f_N^c(u, v)$ with respect to image $f_N^e(x, y)$ are 2D procedures. That is why their computation complexity is significantly higher than the computation complexity intrinsic to their 1D analog. Due to this fact, it is of interest to develop quick algorithms for estimating the shift of 2D images, the computation burden of which is close to the computational burden intrinsic to the 1D algorithm.

To solve this problem, it is suggested to use a method for separating the 2D shift onto two independent 1D ones that makes it possible to process 1D arrays instead of 2D ones.

The separation is performed by calculating the cyclic invariants for each line and each column (a kind

The results of algorithm simulation for images matching according to the measure of similarity MAD with different strategies for searching for a global extremum

Strategy for searching for a global extremum	Tested flow	The way to estimate the video frame shift for a jet flow		The error of algorithm operation		The time of algorithm operation (ms)
		by hand (pixels)	algorithmic (pixels)	absolute (pixels)	relative %	
Total search	1	333	334	1	0.3	4073
	2	328	328	0	0	
	3	340	342	2	0.58	
Three-step search	1	333	318	15	4.5	79
	2	328	340	12	3.66	
	3	340	352	12	3.53	
Hexagonal search	1	333	326	7	2.1	53
	2	328	320	8	2.44	
	3	340	335	5	1.47	
Cross-hexagonal search	1	333	336	3	0.9	28
	2	328	326	2	0.61	
	3	340	344	4	1.18	

of generalized projection (shadows) of the 2D image onto two mutually normal directions). A particular case of this method is the procedure for generating an ordinary "shadow," to summarize all elements for lines and columns.

Let $f(x, y)$ be the brightness function of a certain image, $x, y = \overline{0, N-1}$, $S(\cdot, \cdot, \ldots, \cdot)$ be a symmetric function with respect to N variables (for example, $\sum_{x=0}^{N-1} \bullet$), and $\{U_\omega(\bullet, \bullet, \ldots, \bullet) | \omega = \overline{1, K}\}$ be an arbitrary set of K functions with respect to l variables. Let us take l arbitrary horizontal countings $f(x_1, y)$, $f(x_2, y)$, ..., $f(x_l, y)$, and let us calculate as follows:

$$\begin{gathered} I^y_\omega(f(0, y), f(1, y), \ldots, f(N-1, y)) \triangleq S \\ \times U_\omega[f(x_1, y), f(x_2, y), \ldots, f(x_l, y)], \\ U_\omega[f(x_1 \oplus 1, y), f(x_2 \oplus 1, y), \ldots, f(x_l \oplus 1, y)], \ldots, \\ U_\omega[f(x_1 \oplus (N-1), y), f(x_2 \oplus (N-1), y), \ldots, \\ f(x_l \oplus (N-1), y)], \end{gathered}$$

where $\oplus$ means summarizing over mod N. If the whole array $\{f(0, y), f(1, y), \ldots, f(N-1, y)\}$ is shifted cyclically, there is change of variables $U_\omega[\ldots]$ inside symmetrical function S, which does not change its value. The value

$$I^y_\omega \triangleq I_\omega(f(x, y)) = I_\omega(f(0, y), f(1, y), \ldots, f(N-1, y))$$

we call an invariant of y-th column for image $f(x, y)$. A set of invariants I^y_ω under $\omega = \text{const}$, $y = \overline{O, N-1}$ forms a 1D array, a line, and we call it an invariant projection for columns with number ω. For a similar invariant line projection, we use the designation I^x_ω.

CONCLUSIONS

If we separate the motion of the 2D object into mutually orthogonal directions, it becomes possible to estimate the shift by means of the 1D method, for example, MAD, independently of each other. If we use this approach for estimating the rate of motion for the jet flowing out of the melting furnace, it makes possible to reduce the time of algorithm operation down to 8 ms, to estimate on-line the melt discharge, and to do it in television standard.

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